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Synergistic Enhancement of Lithium-Ion Battery Anodes: A Comprehensive Study of SiO₂, GO and GO–SiO₂ Hybrids



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Abstract: Silicon dioxide (SiO₂) is considered a promising next-generation anode material for lithium-ion batteries due to its chemical stability, natural abundance, and low cost. However, its practical use is limited by its inherently low electrical conductivity and modest capacity. To address these limitations, graphene oxide (GO) has emerged as an effective additive for improving the performance of high-energy anodes. In this study, commercially relevant GO-based materials including GO nanosheets, SiO₂ nanoparticles, and GO–SiO₂ hybrid composites, were comparatively evaluated for lithium-ion battery applications. While GO nanosheets offer a large surface area, their tendency to re-stack restricts ion transport, resulting in poor electrochemical behavior. SiO₂ nanoparticles display good chemical stability and acceptable cyclability (~50% retention), yet suffer from poor conductivity and limited capacity. The GO–SiO₂ hybrid electrode demonstrated improved first-cycle Coulombic efficiency and exhibited the lowest initial capacity decay among the tested materials, although its long-term cycling stability still requires enhancement. To overcome the shortcomings of individual SiO₂ and GO–SiO₂ systems, a modified strategy for GO-based anodes was explored, achieving notable improvements in battery performance, cycling stability, electrical conductivity and capacity retention.

Introduction

To address the intrinsic limitations of conventional anode materials, graphene oxide (GO) has emerged as an effective functional additive for lithium-ion battery (LIB) applications (Lin et al., 2015; Shi et al., 2016; Cong et al., 2021a&b; Chen et al., 2021; Khan et al., 2024). GO is a two-dimensional carbon material rich in oxygen-containing functional groups, offering improved electrical conductivity, high surface area, and excellent mechanical strength (Liang et al., 2024). These features enable GO to function as a conductive framework that enhances electron transport and suppresses agglomeration of silicon dioxide (SiO₂) nanoparticles (Liu et al., 2011; Wu et al., 2012; Liu et al., 2024; Ratsameetammajak et al., 2022).

Consequently, recent research has focused on GO–SiO₂ nanocomposites, where SiO₂ nanoparticles are uniformly dispersed and strongly anchored onto GO

sheets (Sonn et al., 2018; El-Khodary et al., 2021; Brahma et al., 2025). This hybrid architecture improves electrical conductivity while simultaneously alleviating mechanical stress and buffering volume changes during repeated lithiation and delithiation cycles (Huang et al., 2014; Huang et al., 2025). As a result, GO–SiO₂ hybrid anodes exhibit enhanced specific capacity, superior cycling stability, and improved rate capability compared to their individual components (Chuong et al., 2024).

Despite these advancements, GO–SiO₂ hybrid materials still face challenges related to interfacial compatibility, long-term structural durability, and scalable synthesis (Khan et al., 2024). To overcome these limitations, various strategies such as surface functionalization, controlled hybrid assembly, and optimized synthesis routes have been explored (Yan et al., 2025; Jin et al., 2025). Tailoring the composition, morphology, and structural configuration of GO–SiO₂



hybrids has proven effective in further enhancing electrochemical performance (Yu et al., 2024).

In this context, the present study provides a systematic comparison of SiO₂ nanoparticles, GO nanosheets, and GO–SiO₂ hybrid composites as advanced anode materials for LIBs. Key electrochemical parameters, including specific capacity, cycling stability, and rate performance, are comprehensively evaluated. The influence of hybrid structures on volume-change mitigation, electron transport pathways, and mechanical robustness is also examined (Kim et al., 2025). The findings of this work aim to support the rational design of next-generation high-energy anodes based on GO–SiO₂ hybrid architectures.

Although significant progress has been achieved, challenges related to interfacial interactions, structural reliability, and cost-effective large-scale synthesis remain (Khan et al., 2024). Ongoing research emphasizes surface engineering, optimized hybrid assembly, and advanced synthesis methodologies to unlock superior electrochemical performance (Cong et al., 2021b; Jin et al., 2025). Overall, this study delivers a detailed evaluation of SiO₂, GO and GO–SiO₂ hybrid anodes, highlighting structure–property relationships critical for the development of high-performance, long-life lithium-ion batteries (Kim et al., 2025).

Electrode Materials for Lithium-Ion Batteries

The development of high-performance lithium-ion batteries requires advanced anode and cathode materials with higher capacity, improved stability, and extended cycle life. Graphite (LiC₆), the most widely used commercial anode material, possesses a theoretical capacity of 372 mAh g⁻¹ and a typical energy density of approximately 250 Wh kg⁻¹ (Khan et al., 2024). Its excellent stability, safety, and low cost have enabled widespread adoption in portable electronics and electric vehicles. However, the limited capacity of graphite has driven the search for next-generation anode materials.

Silicon has emerged as a highly promising alternative due to its exceptionally high theoretical capacity of approximately 4200 mAh g⁻¹, resulting from the formation of lithium-rich silicide phases during lithiation (Kim et al., 2008; Li et al., 2021; Cong et al., 2021a&b; Jiang et al., 2022; Liang et al., 2024). Despite this advantage, silicon undergoes severe volume expansion of nearly 300%, leading to particle pulverization, loss of electrical contact, and rapid capacity degradation (Khan et al., 2024). To mitigate these challenges, research has focused on nanostructuring silicon, forming silicon–carbon composites, and developing hybrid architectures

capable of accommodating volumetric changes (Cong et al., 2021a; Kim et al., 2025).

Lithium titanate (Li₄Ti₅O₁₂) represents another commercially viable anode material. Although its theoretical capacity (175 mAh g⁻¹) and energy density are lower than those of graphite and silicon, lithium titanate offers exceptional safety, fast-charging capability, and remarkable cycling stability, making it suitable for applications requiring long service life and high reliability (Khan et al., 2024).

Graphene has also attracted significant attention as an anode material owing to its two-dimensional structure, high electrical conductivity, and large surface area (Liang et al., 2024). While graphene can theoretically store more lithium than graphite, practical challenges such as sheet restacking and aggregation limit its electrochemical performance. Hybrid materials based on graphene oxide have been developed to overcome these limitations by enhancing dispersion and preventing agglomeration (El-Khodary et al., 2021; Ratsameetammajak et al., 2022).

Tin-based anodes provide another high-capacity alternative, with a theoretical capacity approaching 994 mAh g⁻¹. However, similar to silicon, tin experiences substantial volume expansion during cycling, leading to mechanical failure and rapid capacity loss. Current research emphasizes nanostructuring, carbon compositing, and stress-buffering designs to improve the durability of tin-based anodes (Khan et al., 2024).

Table 1. Theoretical capacity of different anode/cathode materials.

Materials	Theoretical capacity (mAh/g)	Typical Energy Density (Wh/kg)	Level of Development	References
Graphite (LiC ₆)	372	250	Commercialized	Insinna et al., 2023
Silicon (Si)	4200	150-400	Research	Casimir et al., 2016
Lithium Titanate (Li ₄ Ti ₅ O ₁₂)	175	150	Commercialized	Zhang et al., 2021
Graphene	744	150-160	Research	Puttapati et al., 2018
Tin (Sn)	994	250-400	Research	Lokcu et al., 2022

In summary, while graphite remains the dominant commercial anode material, silicon, graphene, and tin offer significantly higher theoretical capacities. Each of these materials faces distinct challenges related to volume expansion and cycling stability. Lithium titanate provides a safer, long-life alternative despite its lower capacity. Continued development of hybrid materials, nanostructured composites, and advanced architectures represents a promising pathway toward achieving the high energy density and durability required for next-generation lithium-ion batteries (Kim et al., 2025; Yu et al., 2024).

Challenges for Si Anodes

Silicon anodes exhibit lithiation and delithiation mechanisms that are fundamentally different from those of conventional intercalation-type electrodes (Cong et al., 2021; Khan et al., 2024). During lithiation, silicon undergoes alloying reactions with lithium, which result in substantial structural and volumetric changes (Liang et al., 2024). This process leads to pronounced volume expansion, while delithiation causes partial volume contraction as lithium is extracted from the silicon matrix. Throughout the lithiation cycle, silicon is also known to pass through multiple distinct crystallographic phase transformations, further contributing to structural instability (Yu et al., 2024).

A major challenge associated with silicon anodes is the extremely large volume expansion that occurs during lithiation, which can reach up to approximately 300% (Khan et al., 2024). Such drastic expansion generates significant mechanical stress within the electrode, leading to cracking, pulverization, and eventual degradation of the anode structure (Cong et al., 2021; Kim et al., 2025). These mechanical failures adversely affect electrode integrity and significantly reduce the cycle life of lithium-ion batteries.

During repeated charge–discharge cycling, silicon or silica-based particles undergo continuous expansion and contraction (El-Khodary et al., 2021; Ratsameetammajak et al., 2022). This repeated mechanical deformation can damage the anode, resulting in loss of electrical contact between active material particles and the current collector. Additionally, the formation of an unstable solid–electrolyte interphase (SEI) layer further accelerates performance degradation (Brahma et al., 2025). Both

loss of electrical connectivity and unstable SEI growth contribute directly to rapid capacity fading and shortened battery lifespan (Chuong et al., 2024).

With prolonged cycling, silicon anodes commonly exhibit progressive capacity loss. This degradation is largely attributed to the continuous growth and rupture of the SEI layer, which irreversibly consumes lithium ions and reduces the amount of lithium available for electrochemical reactions (Jin et al., 2025). Over time, the repeated breakdown and reformation of the SEI layer lead to increased impedance and further deterioration of electrochemical performance (Huang et al., 2025).

Silicon anodes also tend to exhibit a relatively low initial coulombic efficiency. During the initial charge–discharge cycles, a significant fraction of lithium ions is irreversibly consumed in forming the SEI layer, resulting in energy loss (Cong et al., 2021; Khan et al., 2024). Although silicon is inherently more conductive than graphite, this advantage is offset by lithium consumption during SEI formation, which reduces the effective capacity in early cycles (Liang et al., 2024).

Furthermore, repeated lithiation and delithiation can lead to severe material degradation, including particle fracture, pulverization, and structural collapse (Yu et al., 2024; Kim et al., 2025). These processes weaken the mechanical stability of the anode and ultimately diminish electrochemical performance and reduce the structural integrity of the electrode (Khan et al., 2024).

Electrochemical Performance Testing

Electrochemical performance testing plays a vital role in assessing the suitability of materials, such as the SiO₂-GO hybrid, for energy storage applications, such as lithium-ion batteries. These tests help analyze the electrical conductivity, charge-discharge behavior, and overall efficiency of the material when used as an electrode.

Cyclic Voltammetry

The CV plot compares the electrochemical behavior of three materials: Among them these are Silicon Dioxide (SiO₂), Graphene oxide (GO) and the composite of GO and SiO₂, SiO₂@GO. On the X-axis, the applied potential (V) in relation to the Standard Calomel Electrode (SCE) is shown. In contrast, the Y-axis represents current density (mA/cm²), which reflects electron transfer efficiency.

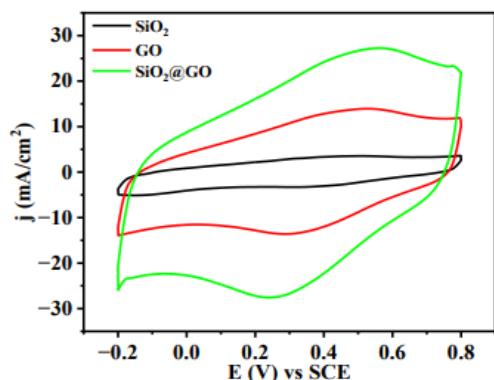


Figure 1. Cyclic Voltammetry (CV) Analysis.

- **SiO₂:** There is the least current density ($\sim \pm 10$ mA/cm²) making this phase to have the least of all electrochemical activity because it is non-conductive.
- **GO:** Demonstrates slightly higher current density (on and off ± 15 mA/cm²), which proves that more efficient electron transfer occurs because of the conductive graphitic structure of the working electrode.
- **SiO₂@GO Hybrid:** Acheret $\sim \pm 30$ mA/cm² shows the highest condition current density. This reveals that GO's conductivity and the structural stability of SiO₂ increase the number of redox sites, hence improving electrochemical performance.

The analysis also shows that the presence of SiO₂ within the GO matrix improves charge storage and electron-transfer properties compared with SiO₂ and GO alone, making it suitable for Li-ion battery applications.

Electrochemical Impedance Spectroscopy (EIS) Analysis

A Nyquist plot obtained through Electrochemical Impedance Spectroscopy (EIS), which is the graphical representation of the impedance characteristics, mainly in battery literature but can be applied to other fields as well.

Nyquist Plot Analysis

- **X-axis:** Real part of impedance (Z' , ohm) that defines resistive properties of an element.
- **Y-axis:** Reactive component of impedance (Imaginary part of impedance Z'' , expressed in ohms).
- **Shape of the curve:** Correlates with electrochemical activities at various frequencies.

Silicon Dioxide (SiO₂)

- **Impedance:** Low drive current medium power dissipation ($\sim 25 \Omega$ ON Z' and 23Ω O Z'').
- **Interpretation:** SiO₂ exhibits low conductivity and high electrical resistivity and thereby suppresses

electron transfer. But it's not suitable for efficient charge transfer applications.

Graphene Oxide (GO)

- **Impedance:** Medium load (~ 1820 on Z' and 2000 on Z''). Interpretation: It was found that GO has higher conductivity than that of SiO₂, but some of the insulating groups exist in the structure. It works on a higher efficiency compared to SiO₂ but may also encounter the similar problems and with a rate of charge transfer.

SiO₂@GO Hybrid

- **Impedance:** Lowest impedance $\sim 15 \Omega$ on Z' and 10Ω on Z'' both are very low.
- **Interpretation:** With GO's conductivity and SiO₂'s stability, the hybrid ww provides the highest charge transfer and conductivity suitable for high-performance applications in batteries such as lithium-ion batteries.

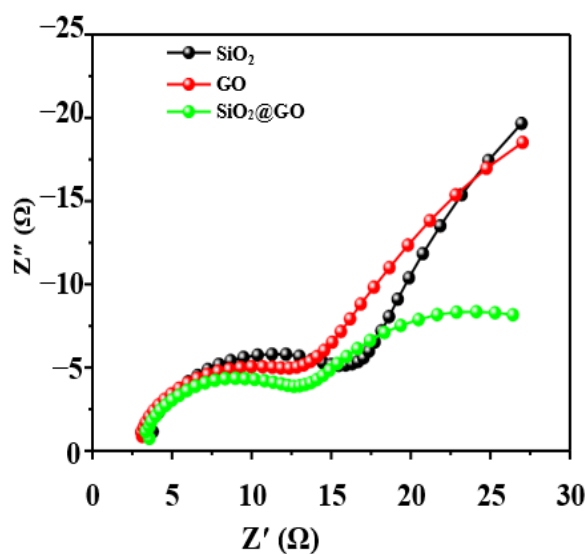


Figure 2. Electrochemical Impedance Spectroscopy (EIS) Analysis.

Key Observations

- **SiO₂:** Highest value of impedance, lower conductivity.
- **GO:** Higher than that of SiO₂ but still modest, intermediate impedance.
- **SiO₂@GO Hybrid:** The lowest impedance, making it suitable for applications that require fast charge transfer and energy storage.

Galvanostatic Charge-Discharge (GCD)

Galvanostatic Charge-Discharge (GCD) curve for three materials: SiO₂, Graphene Oxide, GO-SiO₂ hybrid material SiO₂@GO. Galvanostatic Charge-Discharge (GCD) Analysis comparing the voltage response over time for three materials:

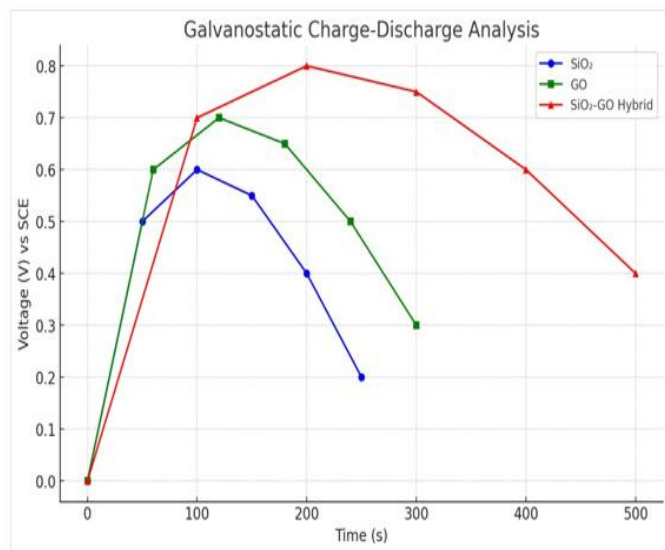


Figure 3. Galvanostatic charging-discharging analysis.

Nyquist Plot Analysis

- X-axis: Real part of impedance (Z' , Ohm) that describes how something behaves like a resistor.
- Y-axis: The capacitive or inductive component of impedance, because impedance has both magnitude and phase, the real part is resistance (R , Ω).
- Shape of the curve: Represents an electrochemical phenomenon at various frequencies.

Silicon Dioxide (SiO₂)

- Impedance: High impedance ($\sim 25\Omega$ on Z' and 23Ω on Z'').
- Interpretation: SiO₂ possesses extremely low conductivity and has high resistivity and thereby there is poor electron transport ability. It is clearly unfit for usage in efficient charge transfer applications. Graphene Oxide (GO):
- Impedance: Ubigeña broadband implementations: moderate impedance (approx. 18Ω on Z' , 20Ω on Z'').
- Interpretation: GO has better conductivity than SiO₂ but still keeps some of the insulation characteristics. Compared to SiO₂, it is more effective but could potentially be limited by resistance and charge transfer rate.

SiO₂@GO Hybrid

- Impedance: Lowest impedance of MLM $\sim 15\Omega$ on Z' and 10Ω on Z'' lowest impedance is $\sim 5 \times 10^{-3}$ on Z' and 3.3×10^{-3} on Z'' .
- Interpretation: The features that make this hybrid favorable include the very high conductivity of GO and the stability of SiO₂, making the material appropriate for high-performance uses, such as lithium-ion batteries.

Key Observations

- SiO₂: When it comes to impedance, there is nothing better than having the highest impedance and the lowest conductivity.
- GO: The impedance is moderate, as it is between the material SiO₂ and the ideal value.
- SiO₂@GO Hybrid: uses the least amount of impedance and is a nice fit for fast charging and energy storage processes.

The SiO₂@GO hybrid outperforms SiO₂ and GO, demonstrating superior electrochemical properties and suitability for applications requiring efficient electron and ion transfer.

Specific Capacity

Comparative analysis of the specific capacity in the 101st cycle for SiO₂, GO and SiO₂-GO Hybrid A trend is observed, a decrease in proliferation of specific capacity over the 100 cycles of analyzed compound, because of a number of factors, such as formation of a stable solid electrolyte interphase film, mechanical degradation, and loss of active material.

- SiO₂ initially possesses the highest specific capacity of 953 mAh/g but the capacity fades rapidly in subsequent cycles to 511 mAh after 100 cycles. Such, for SiO₂-GO Hybrid, the initial capacity is at 810 mAh/g and by and large mainly oscillates, the final value being at 731 mAh/g. The following is a record of the specific capacity with GO: Among them, the capacity drops from an initial 790 mAh/g to 630 mAh/g and its decline rate is lower than that of SiO₂, cline, reaching 511 mAh/g by the 100th cycle.
- SiO₂-GO Hybrid begins at 810 mAh/g and maintains a relatively stable capacity over cycles, ending at 731 mAh/g.
- GO starts at 790 mAh/g and also declines, but at a slower rate than SiO₂, ending at 630 mAh/g. This analysis is referred to as cycle stability because it examines the interactions between nodes and the feedback from cycles formed by a node relative to other nodes in the graph.

Graph Analysis (Cycle Stability)

X-Axis (Cycle Number): Stands for the cycle numbers, which denote the lifetimes of each material as an anode material of LIBs.

- Y-Axis (Specific Capacity in mAh/g): The ability to store a charge relative to the amount of energy stored is also quantified for each material.

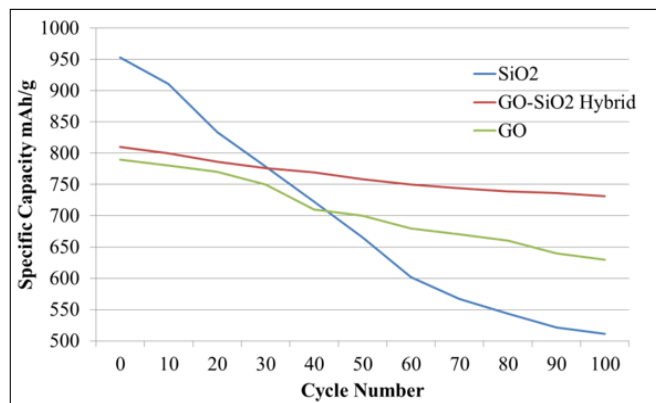


Figure 4. Specific capacity over 100 cycles for SiO₂, GO and SiO₂-GO hybrid materials

Performance Comparison

Silicon Dioxide (SiO₂):

- Has the highest initial specific capacity to go with it, the highest capacity decay rate. Large decrease indicates capacity fading problems because of the silicon's volume change during cycles, which leads to mechanical failure and material loss.
- It confines the practical application of SiO₂ for long-term application as the capacity reduces to almost 50% of the initial value for 100 cycles.

Graphene Dioxide (GO):

- While the capacity of GO-based electrode material is lower than that of pure SiO₂, the rate of degradation of the capacity of GO-based electrode material slows down gradually with the increase in cycles.
- An improvement of stability is noted from the SiO₂ structure with a discussion of the fact that the given compound is not as stable as the hybrid material.
- At 630 mAh/g, capacity retention is higher in GO as compared to SiO₂, however, it may not be enough in terms of cycling performance for high-energy applications.

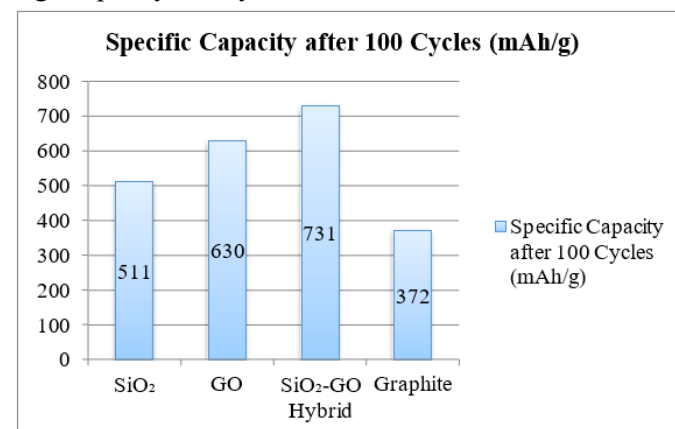
SiO₂-GO Hybrid:

- Although the hybrid material has an initial capacity that is slightly worse than that of pure SiO₂, it shows much better performance in terms of stability and steady degradation. The final achieved capacity of 731 mAh/g remains stable across cycles, thus showing the good solvation of silicon's expansion problems by the flexible, conductive GO.
- This stability also indicates that there is a focused interaction between SiO₂ and GO and that GO can function as a buffer layer to minimize mechanical stress while increasing the conductivity capacity retention due to silicon's volume expansion during cycles, causing mechanical stress and material degradation.

Table 2. Comparison of Specific Capacity and Cycle Stability for SiO₂, GO, and SiO₂-GO Hybrid.

Material	Initial Specific Capacity (mAh/g)	Specific Capacity after 100 Cycles (mAh/g)	Capacity Retention (%)	Key Observations
SiO ₂	953	511	53.6%	Highest initial capacity but rapid decline due to volume expansion, leading to poor cycle stability.
GO	790	630	79.7%	Moderate stability; gradual decline in capacity, suitable for applications with moderate cycle life needs.
SiO ₂ -GO Hybrid	810	731	90.20%	Best cycle stability; GO mitigates silicon's expansion, enhancing long-term capacity retention and stability.

This highlights that SiO₂-GO Hybrid offers a higher capacity with relatively strong retention, making it a promising alternative for applications requiring both high capacity and cycle life.



Graph 1. Comparative analysis of Specific capacity over 100 cycles for SiO₂, GO and SiO₂-GO hybrid materials.

Capacity Retention

Cycle retention is the ability to express as percentage of the initial specific capacity that is

retained after a given number of charge-discharge cycles. Playing an important role in lithium-ion batteries used in devices that require long-term stability and constant power reserve, it indicates the state of charge preservation.

$$\text{Capacity Retention (\%)} = \left(\frac{\text{Specific Capacity after 100 Cycles}}{\text{Initial Specific Capacity}} \right) \times 100$$

1. SiO₂

$$\text{Capacity Retention of SiO}_2 = \left(\frac{511}{953} \right) \times 100 \approx 53.6\%$$

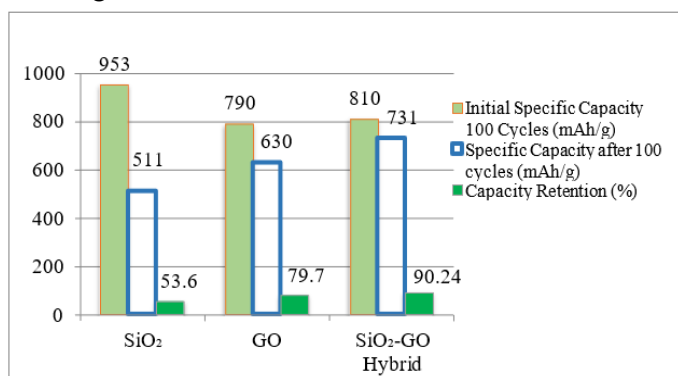
2. GO

$$\text{Capacity Retention of GO} = \left(\frac{630}{790} \right) \times 100 \approx 79.7\%$$

3. SiO₂-GO Hybrid

$$\text{Capacity Retention of SiO}_2\text{-GO Hybrid} = \left(\frac{731}{810} \right) \times 100 \approx 90.2\%$$

- SiO₂ has a very low cycling efficiency at around 53.6% after 100 cycles and degrades very fast due to the devolatilization of silicon in the operation that causes mechanical stress.
- GO electrode retains nearly 79.7% of its capacity, which indicates better stability than the CNFs because of the conductive network and flexibility of the GO sheets that minimize the loss of electrical contact during the cycling process.
- SiO₂-GO Hybrid exhibits 90.2% capacity retention due to the synergistic effects of SiO₂ for structural stability, GO for conductivity and flexibility and degradation.



Graph 2. Comparative Analysis of Specific Capacity with Retention capacity Over 100 Cycles for SiO₂, GO and SiO₂-GO Hybrid Materials.

Key Observations

- SiO₂ (53.6% retention): Poor cyclic stability is prevalent due to the highly volatile silicon that quickly experiences a rapid capacity fade on account of its volume.
- GO (79.7% retention): It can afford the anode structure with a conductive network, which can enhance its stability slightly, slightly worse than SiO₂-GO Hybrid.
- SiO₂-GO Hybrid (90.2% retention): SiO₂ enhances structural stability while GO provides flexibility, conductivity and achieves the highest

retention rate of all the samples prepared. Consequently, it has been identified that the SiO₂-GO Hybrid is the best material suited for lithium-ion battery anode due to both the impressive initial capacity and good cyclic stability.

Conclusion

This research effectively mitigates the problems associated with anodes made from graphite and silicon for the LIBs through the creation of a binary anode material made of SiO₂ and GO. The research was based on furthering the developments made in stability, specific capacity and cycle life of the material through the integration of the structurally stable SiO₂ and electrically conductive GO.

#The SiO₂-GO hybrid material demonstrated a significant specific capacity of 731 mAh/g compared to theoretical graphite's 372 mAh/g. This indicates a substantial improvement in the battery's ability to store energy.

#Enhanced Stability: The SiO₂-GO hybrid shows improved long-term cycling stability compared to standalone SiO₂ or GO, achieving a high-capacity retention rate of around 90.2% after 100 cycles.

#Mitigated Silicon Expansion: Thus, the incorporation of SiO₂ and GO into the electrode successfully addresses silicon's problem of volume expansion, which leads to a decrease in capacity fading for the electrode during cycling. In volume change conditions that lead to mechanical stress in pure Si-based materials, GO's flexibility and conductive network are useful. This gives durability and capacity retention through the cycles required by the EV batteries.

#Thermal Stability and Electrochemical Performance: The SiO₂-GO hybrid material exhibited superior thermal stability and retained high specific capacity after cycling, achieving 731 mAh/g after 100 cycles, which represents a substantial improvement over SiO₂'s 511 mAh/g capacity after 100 cycles. This aligns with the objective to enhance LIB performance for EV applications, meeting the need for high energy density, stable cycling and thermal durability.

Conflict of interest

None

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